Food Bioprocess Technol (2014) 7:1928–1937
DOI 10.1007/s11947-014-1298-6

ORIGINAL PAPER

Cost Analysis and Environmental Impact of Pulsed Electric Fields and High Pressure Processing in Comparison with Thermal Pasteurization

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Received: 8 May 2013 / Accepted: 10 March 2014 / Published online: 3 April 2014

Abstract The cost of high pressure processing (HPP) and the environmental impact of pulsed electric fields (PEF), HPP and thermal pasteurization of orange juice were estimated in the US. The cost analysis was based on commercial processing conditions that were validated for a 2-month shelf-life of orange juice under refrigeration conditions. Total electricity consumption was estimated to be 38,100 and 1,000,000 k Wh/year for thermal and HPP processing, respectively. Total pasteurization cost of HPP was estimated to be 10.7 ¢/l for processing 16,500,000 l/year (3,000 l/h). Of this, capital costs accounted for 59 % (6.3 ¢/l), labor costs accounted for 37 % (4.0 ¢/l) and utility charges, mainly electricity, accounted for 4 % (0.4 ¢/l). The total HPP cost was 7-folds higher than that of conventional thermal processing (1.5 ¢/l). The equivalent CO_2 emission was 90,000 kg for thermal processing and 700,000 and 773,000 kg for PEF and HPP, respectively. This corresponds to an increase between 7- and 8-folds in comparison to the thermal processing. Increasing the production output by 2- to 6-folds reduced the total production costs of nonthermal processing by 50–75 %. A deeper knowledge of the processing costs and environmental impact of nonthermal technologies will afford companies a better understanding of the benefits and limitations of these novel systems.

Keywords Cost analysis · Environmental impact · High pressure · Pulsed electric fields · Thermal processing

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Introduction

During the last decade there has been a tremendous research effort on the application of physical nonthermal technologies (namely pressure, electrical and irradiation based technologies) for food processing and more than 3,000 articles have been published in peer-reviewed SCI indexed journals in the food science and technology field (Web of Knowledge 2012). The main driving force for the research development seen in this area has been consumers demand for safer, fresher, natural and more nutritious food. The published data have shown the ability of these technologies to inactivate pathogenic and spoilage microorganisms at near-ambient temperatures and extend the overall shelf-life at refrigeration temperatures, avoiding thermal degradation of the food components, and consequently preserving the sensory and nutritional quality of the fresh-like character of food products. These advances have moved the food industry to successfully adopt these technologies for specific market niches (Pereira and Vicente 2010).

An extremely important factor which needs to be taken into account before fully implementing these emerging technologies into an industrial setting is the cost. High pressure processing (HPP) was one of the first nonthermal technologies to be commercialized. Since the 1990s, there has been an exponential growth of HPP industrial applications and in 2008 alone there were 125 HPP units installed in over 60 companies producing 250 different HPP-treated products (Tonello 2011). The industrial units ($770,000 for 55 l and $3,150,000 for 420 l) provide pressures up to 600 MPa at room temperature with a maximum overall production around 5000 kg/h depending on the holding time and package size (Tonello 2011). Cost of HPP will depend on the total cycle time (pressure come up, holding and loading/unloading times), vessel filling ratio, energy, labor and capital costs (Mujica-Paz et al. 2011)

Pulsed electric fields (PEF) technology is an emerging technology where a great research effort has been placed, with new chamber designs making it possible to apply a uniform electric field in large-scale equipment (Huang and Wang 2009; Toepfl et al. 2006). Several pilot-plant-scale units have been developed by different research groups with flow rates of 400–2,000 l/h (Min et al. 2003a, b) and commercial-scale PEF units for food processing with an overall flow rate of 400–6,000 l/h (Kempkes 2011). The use of PEF by the juice processing industry became a reality in the USA where several types of fruit juices treated by PEF were commercialized by Genesis Juice Cooperative (Clark 2013); however, this firm subsequently switched from PEF to HPP for undisclosed reasons. Cost of PEF processing will be greatly dependent on the capital cost and energy consumption.

Despite the large quantity of scientific data available in the literature, the development of systematic cost analysis studies of the commercial application of these technologies is still scarce. Some studies report the cost of HPP (5–22 ¢/l) and PEF (4–7 ¢/l) processing (Jin and Zhang 2002; Huang and Wang 2009; Tonello 2011; Ludikhuyze et al. 2002; Mujica-Paz et al. 2011; Thakur and Nelson 1998; Hernando-Saiz et al. 2008; Sampedro et al. 2013) but there are not studies up to date that thoroughly compare the cost of these technologies with traditional thermal pasteurization.

Another important factor when implementing these new technologies is the environmental impact. There is great concern regarding the increase in greenhouse gases and their impact on the environment. This has become more important in recent years due to a greater consciousness of the link between global warming and emissions of greenhouse gases from consumers and the demand for green food products from local producers. Factors such as wastewater, gas emissions and energy consumption have increasingly attracted food processors' attention (Mattson and Sonesson 2003; Pereira and Vicente 2010).

Despite hundreds of studies published showing the benefits of HPP and PEF on the safety and quality of foods, there are no studies available that conduct a robust and extensive cost analysis and environmental impact of these technologies. The methodology and results of such studies would assist companies in the decision-making process with respect to the implementation of these, and other nonthermal, processes.

The objective of the present study was to analyze the cost and environmental impact of orange juice processed by PEF, HPP and thermal systems. Orange juice was chosen due to its high consumption and wide commercialization around the world. As the raw material cost of the orange juice was not included in the analysis, the selection of other juices would have a negligible impact on the overall cost and environmental impact.

Material and Methods

Orange Juice

Valencia oranges were purchased from a local supermarket and stored at 4 °C for 24 h prior to squeezing. Before squeezing, oranges were visually inspected to remove moldy and damaged oranges, and about 20–30 unblemished oranges were washed at a time in a 5-l bucket with tap water to remove dirt. The washed oranges were squeezed using a juicing machine (Zumex 3; Zumex S.A., Valencia, Spain) followed by filtration with a strainer (mesh size: 1×1 mm) to remove pulp and seeds from the juice. The juice was characterized by a pH of 4.1 and 12° Brix. The freshly squeezed juice was stored in a sterile 15-l bucket at 4 °C prior to use.

High Pressure Treatment

The processing conditions for the high pressure treatment (550 MPa, 90 s, room temperature) were obtained from Hyperbaric S.A. (Burgos, Spain) for the commercial pasteurization of orange juice with a shelf-life of 2 months under refrigeration conditions (4 °C). These conditions should provide an adequate inactivation of concern pathogens in orange juice (*Salmonella* spp., *Escherichia coli* and *Listeria monocytogenes*) based on previous studies (see, e.g., a recent review by Rendueles et al. 2011). All pressure experiments were performed in a laboratory-scale vessel (MINI FOODLAB FPG5620; Stansted Fluid Power Ltd., Stansted, Essex, UK). The pressure medium was a mixture of isopropyl alcohol (Mallinckrodt Baker Inc., Phillipsburg, NJ, USA) and castor oil (Sigma-Aldrich, St. Louis, MO, USA) (90:10 V/V). A thermostated mantel, which surrounds the vessel, was connected to a cryostat keeping the temperature constant during the experiment. Temperature was recorded by a thermocouple (K-type) placed inside the vessel. The samples for the shelf-life study were filled in 40 ml sterile screw-cap centrifuge tubes, double bagged in heat-sealed plastic bags using an AIE-200 impulse heat sealer (American International Electronics, Kenneth City, FL, USA), and enclosed in the pressure vessel already equilibrated at room temperature (25 °C). Pressure was built up at a rate of 200 MPa/min. After the preset hold-time (90 s), the vessel was quickly decompressed. After pressure release the samples were immediately cooled in ice-water and stored at 4 °C.

Thermal Treatment

Treatment conditions for orange juice (85 °C, 5 s) were obtained from Kozempel et al. (1998). The treatment was carried out in a plate and frame heat exchanger (FT74X/HTST/UHT, Armfield Inc., Hampshire, UK). Orange juice sample placed in a feeding tank was driven by a pump to the heat exchanger at 170 ml/min where it was rapidly heated to 85 °C. Then the product reached the holding tube where the treatment conditions (85 °C, 5 s) were maintained. After the treatment, the samples were immediately chilled with cold water (20 °C) in a cooler (FT61, Armfield Inc.), and packaged and stored at 4 °C until needed for analysis.

Shelf-life

A shelf-life study was conducted at 4±1 °C for 8 weeks to simulate the commercial shelf-life of thermal and nonthermal high-pressure pasteurized orange juice. The microbial inactivation and growth were determined by diluting the samples in 0.1 % (w/v) sterile peptone water and plating in TSA (BD, Sparks, MD, USA) for mesophillic bacterial counts, MRS agar (Oxoid Ltd, Cambridge, UK) for Lactobacilli, acidified potato dextrose agar (BD) for yeasts and Saboraud agar (Oxoid) for molds every week for 8 weeks. Plates were incubated at 37 °C for 24 h for bacteria, 37 °C for 48 h for *Lactobacillus* and yeast cells, and 32 °C for 5 days for molds.

Cost Analysis

Cost models for two pasteurization systems (thermal with heat recovery and nonthermal HPP) were developed for a medium-size facility pasteurizing 16,500,000 l of orange juice per year with a throughout of 3,000 l/h, 20 h of operation/day (4 h for sanitizing and maintaining the process equipment) and 5,500 h/year. The cost of HHP processing was compared to a PEF pasteurization process with heat recovery (30 kV, 60 °C) for the same throughput and equivalent shelf-life (Sampedro et al. 2013).

The models were developed using SuperPro Designer® Version 8, Build 8 software (Intelligent Inc., Scotch Plains, NJ, USA) and addressed sizing of unit operations, utility consumption and capital and unit pasteurizing costs. The models were based on data gathered from equipment manufacturers, and publicly available scientific literature. Data on cost and energy consumption of all processing units for each technology (pumps, piping, heat exchangers, and other processing equipment) were added to the model as inputs for the desired production size and final cost estimates per unit of volume were calculated as the output of the model. The electricity prices used in this study were based on those reported by the US Department of Energy–Energy Information Agency (DOE–EIA) as average industrial electrical unit rates for 2011 ($0.0689 kW h). The steam charges were based on steam generated in a natural gas boiler as reported by DOE–EIA in 2011 of $5.02/1,000 cubic feet of natural gas delivered to an industrial customer. The energy estimates in the present study are specifically for the US and the processing of orange juice. Energy prices may change by country, region, energy source and food product yielding different absolute cost estimates for energy. However, the relative cost difference among processes (% increase) should remain relatively constant.

Storage of the juice and other processes associated with the juice treatment before or after pasteurization plus the packaging of the juice were not included in our estimates. In addition, costs of water, raw materials and waste treatment were not considered in the model. Also excluded from the capital costs were the charges for common facilities, utilities and offices, environmental controls, land acquisition and site development, working capital and the cost of capital during construction. These costs may not be similar for the different processes and the analysis of these costs are commonly done during later engineering stages of a project.

Depreciation was estimated as either taxable depreciation or economic depreciation. Economic depreciation is used to incorporate the capital charges into operating costs and was estimated as the total capital charges of the facility divided by the product of the estimated number of units of production annually, times the projected economic life of the facility. Taxable depreciation values are estimated by government tax codes and factor into the amount of taxes an organization will pay. Administration charges are ongoing charges incurred during production and are better accounted for on a time basis rather than a specific unit of production. By aggregating these charges and prorating them over the number of items produced per unit of time these charges may be integrated into the unit production costs.

Environmental Impact

Environmental impact of a given process is usually expressed as the production of greenhouse gas levels. In this study, greenhouse gas levels were expressed in terms of carbon dioxide equivalents (kg of CO_2 equivalents). Environmental impact of high pressure, PEF and thermal pasteurization processes was estimated based on the equivalent CO_2 emissions (kg/year) from electricity (equipment, steam and cooling water) and natural gas consumption used in the systems by using conversion factors. Conversion factors were used to determine the amount of greenhouse gases generated during the production and transmission of steam and electricity and were obtained using public available data from the US Department of Energy (Deru and Torcellini 2007). These factors will vary by area and are dependent of the type of fuel used in their generation and prevailing environmental control regulations.

Sensitivity Analysis

A sensitivity analysis was performed to estimate the effect of production output (1,000–5,500 l/h for PEF and 500–3,000 l/h for HPP) on total cost of production (¢/l) taking into account capital, labor and energy requirements for the different production sizes. Different vessel capacities (55–420 l) were used to estimate the cost of HPP at different outputs.

Results and Discussion

Microbiological Shelf-life Study

Fresh squeezed orange juice, HPP-treated (550 MPa, 90 s) and thermally treated (85 °C, 5 s) samples were stored at 4 °C for 2 months. Figure 1 shows the counts of mesophillic bacteria for fresh and treated samples. Treatments reduced the initial background of mesophillic bacteria (2.8 log CFU/ml) by 0.20–0.70 log and *Lactobacillus*, molds and yeasts to below the detection limit (data not shown). Mesophillic counts in thermally processed samples remained constant during the entire storage period (~2.0 log CFU/ml) whereas in HPP-treated samples, they were reduced by ~1.0 log after the first week of storage and progressively lowered until reaching 1.4 log CFU/ml. This reduction may be explained by the effect of acidic environment on pressure-injured cells. This phenomenon is not new and many studies have reported a reduction in microbial counts during the shelf-life of pressure-treated juice samples (see for example Garcia-Graells, Hauben and Michiels 1998; Buzrul et al. 2008). Regarding the untreated control sample, significant increases in mesophillic bacteria (1 log) and molds (3 logs) were observed at the end of the shelf-life, contrary to that observed in the treated samples. *Lactobacilli* counts were gradually reduced in the control sample and reached undetectable levels after the sixth week of storage (data not shown). The shelf-life study validated the commercial conditions for the high-pressure pasteurization of orange juice.

Cost Analysis

The schematic of HPP system designed for commercial pasteurization of orange juice along with process temperatures is shown in Fig. 2. The equipment is standard in industry for the HPP of juices. The juice is first packaged in a suitable container then filled in a plastic basket (assuming a 60–75 % of filling ratio for bottled orange juice) and moved into the high pressure vessel (350–420 l, 380–386 mm diameter, eight pressure intensifiers, 12 cycles/h) for the commercial pasteurization of orange juice (550 MPa for 90 s at room temperature). The pressure and holding time, for the commercial pasteurization of orange juice with a shelf-life of 2 months under refrigeration conditions (4 °C), were recommended by

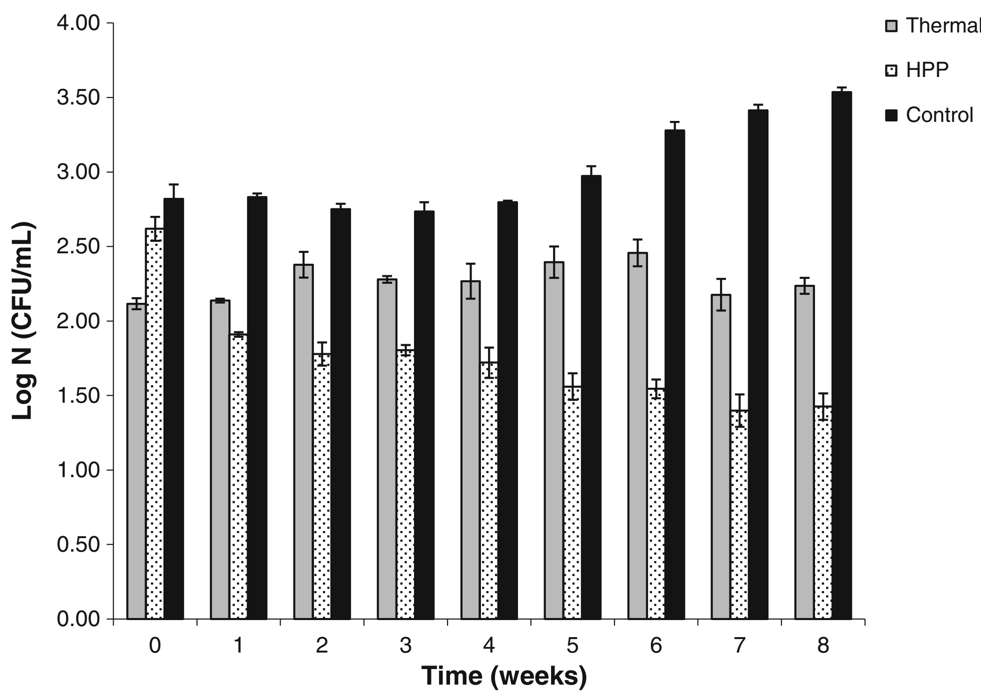

Fig. 1 Counts of mesophillic bacteria in (untreated) control and HPP and thermally processed samples at 4 °C for 8 weeks

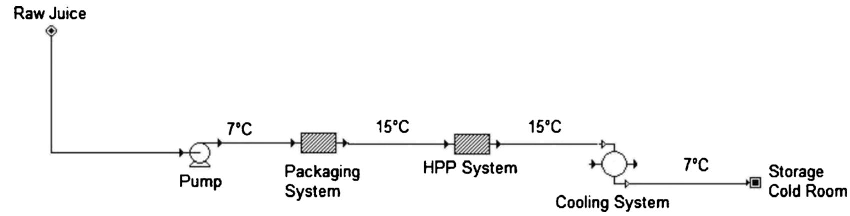

Fig. 2 Schematic of designed commercial HPP system for pasteurization of orange juice

Hyperbaric S.A. (Burgos, Spain), a world leader in HPP equipment manufacturing. The packaged juice is then routed through a cooling system where it is cooled down to 7.0 °C before being placed in a cold storage room. It is worth mentioning that heat recovery is not utilized in this system as temperature returns to its initial value after decompression (due to the adiabatic heating process).

As a means of comparison, Fig. 3 shows the production line of the commercial thermal pasteurization of orange juice at 85 °C for 5 s. In the first stage, the hot juice (85 °C) leaving the pasteurization process heats up the cold (7.0 °C) raw incoming juice to 79.5 °C. This regeneration step minimizes operating costs by reusing thermal energy (~90 %) from the pasteurized stream (Kozempel et al. 1998). From the holding tube, the treated juice (85 °C) is pumped to the regeneration heat exchanger, where the incoming unpasteurized juice cools the pasteurized juice down to 15.4 °C. The pasteurized juice is then routed through a third heat-transfer section where it is chilled to 7.0 °C before the packaging step and further storage. Process pumps, control devices, clean in place equipment and other devices not mentioned above are also required in this and the high-pressure pasteurization system to maintain the proper flow conditions and system cleanliness.

Capital Costs

Table 1 shows the detailed capital costs for HPP and thermal processes. Capital cost for an industrial scale thermal pasteurization system ($66,000) was estimated based on the equipment (plate heat exchangers, pumps and holding tube) necessary to process juice at 88 °C with a hold time of 5 s at a production rate of 16,500,000 l/year (3,000 l/h). The time and temperature conditions are typical for commercial pasteurization of fruit juices (Kozempel et al. 1998). The pasteurization system is very common and has been used by nearly all thermal processors of juices.

The estimated cost to purchase a proprietary HPP system was $2,500,000 taking the average value of two commercial equipment models from two different equipment suppliers available in the market that reached the desired throughput of 3,000 l/h (320- and 420-l vessel). The equipment cost of the supplemental pumps, coolers and heat exchangers was estimated to be an additional $45,000.

The costs mentioned above are for purchasing the equipment needed for the different pasteurization systems. In addition to these charges, additional costs are incurred in installing the equipment and commissioning it, providing the necessary piping, electrical and process control systems as well as foundations, the necessary utility equipment and building to house the equipment. Engineering will be required to provide a design to integrate the system into the other industrial processes and project and construction management will be required to coordinate all of the activities. The extent of these costs can only be determined after the final design is completed for a specific facility and installation factors are commonly used to estimate these costs until the final engineering is complete. We have estimated the total capital costs as being equal to twice the equipment costs through the application of an installation factor of capital costs to equipment costs equal to 200 % (Bauman 1964; Jelen and Black 1983; AACE 1990). This factor may change depending on individual company and project.

The capital costs for the two systems are estimated to be $132,000 for the thermal pasteurization system (0.08 ¢/l) and $5,090,000 for the high pressure system (3.1 ¢/l). In a previous study (Sampedro et al. 2013) we estimated the capital cost

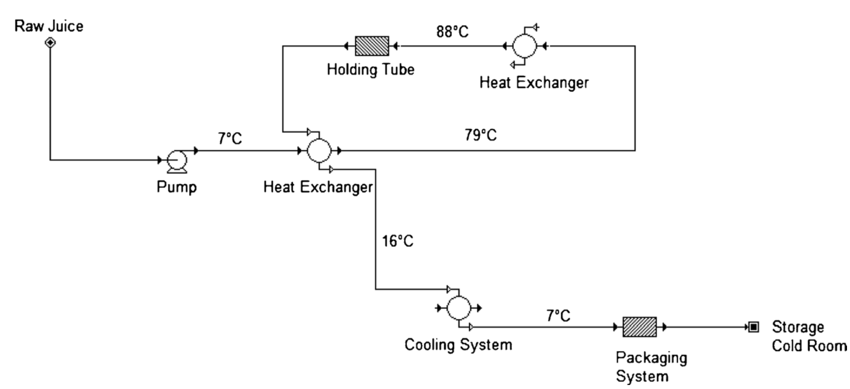

Fig. 3 Schematic of designed commercial thermal system for pasteurization of orange juice

Table 1 Capital cost of thermal and high pressure processes

Process parameters	Unit of measure	Thermal	High pressure
Process flow	l/year	16,500,000	16,500,000
Heat exchanger	$	18,000	2,000
High pressure equipment	$	–	2,495,000
Process chillers	$	31,000	31,000
Holding tube	$	5,000	–
Process pumps	$	12,000	12,000
Total equipment cost	$	66,000	2,545,000
Installation costs (200 %)	$	66,000	2,545,000
Total capital cost	$	132,000	5,090,000
Capital cost	$/l	0.0008	0.031

of a PEF system (monopolar, square wave pulses, three pairs of chambers with heat recovery) designed for the commercial pasteurization of orange juice for the same throughput to be $2,100,000 (1.3 ¢/l). This corresponds to an increase of 16-fold (PEF) and 38-fold (HPP) with respect to the capital cost of the thermal system.

Capital costs of these new technologies correspond to high percentage of the total costs and a reduction in equipment cost over time would impact the total production costs. Gaudreau et al. (2005) employed by a manufacturer of PEF systems, pointed out that the capital cost of PEF could be decreased by a factor of two or more in the future by changing some aspects of the equipment design (monopolar operations, simplified power supplies, smaller treatment chamber gaps and higher pulse frequency). The capital costs for high pressure pasteurization should also decrease over time due to higher demand of pressure units which would allow to "pre-buy" raw materials more easily (Nick de Pinto, personal communication 2012).

Unit Production Costs

Table 2 shows the energy costs associated with each process. Utility charges for thermal pasteurization (natural gas and electricity) accounted for $8,000 per year, corresponding to 3 % of the total cost (0.05 ¢/l). The thermal pasteurization with heat integration has a 96 % heat recovery rate, requiring less energy than a process without that recovery. This is a common practice in the food industry due to the reduction of 90 % in the total steam and electrical energy costs. In the case of the HHP system, the energy consumption was estimated to be 1,020,100 kW h/year ($70,000) corresponding to 4.0 % of the pasteurization costs (0.42 ¢/l). This is 86 % more costly than production costs for thermal processing. Total energy cost of PEF system ($69,000 per year for electricity and cooling water) or 11 % of the total costs are very similar to the high

Table 2 Production costs of thermal and high pressure processes

Process parameters	Unit of measure	Thermal	High pressure
Electricity			
Pumps	kW h/year	2255	2261
Refrigeration units	kW h/year	35,900	33,300
High pressure unit	kW h/year	–	984,500
Total Electricity	kW h/year	38,100	1,020,000
Electrical Costs	$	3,000	70,000
Steam			
Total steam	MT/year	284	–
Steam costs	$	5,000	–
Total energy costs	$/year	8,000	70,000
Labor costs			
Plant operators per shift		1	3
Labor costs	$/h	40	40
Total labor costs	$	220,000	660,000
Facility-related costs			
Estimated plant life	year	10	10
Maintenance charges	%	2.0	8.0
Other administration charges	%	2.5	2.5
Depreciation	$	13,000	508,000
Maintenance and admin charges	$	6,000	533,000
Total annual costs	$/year	247,000	1,771,000
Unit pasteurization cost	$/l	0.015	0.107

pressure system; however, the energy requirements for cooling in the PEF system were higher (Sampedro et al. 2013).

The energy costs of the high pressure system come mainly from the pressure pumps and better pump energy efficiency would reduce the overall production costs. In case of the pulse electric field technology, it is anticipated that energy costs would be reduced over time by minimizing the wasted pulse energy. This typically means very fast switching times (energy in the rise and fall of the pulse is wasted) and flattop of the voltage pulse (so voltage/energy per pulse can be reduced to the minimal level) (Michael Kempkes, personal communication 2011). However, since the energy costs only contribute to a small proportion of the overall costs of these technologies, the potential reduction in production cost would be minimal (50 % reduction on energy costs would reduce only 2 % of the overall costs).

Labor Costs

Labor costs were estimated based on a conservative figure of one operator full time for the thermal processing unit, accounting for over 89 % (1.33 ¢/l) of the thermal pasteurization costs (Table 2). That means labor cost has a great impact on the overall cost production in the thermal system, but recognizing this may be a conservative estimate since some operators may be spread over different operations. A 50 % reduction in the operators' labor costs to half operator ($110,000 to $65,000 per year) would result in a 55 % decrease in the overall costs of thermal pasteurization.

High pressure is considered a batch process where additional labor for product load and unload operations is required. We have conservatively estimated three operators for 3,000 l/h throughput as compared to a single operator for a continuous process. In this process, the labor accounted for 37 % of the total pasteurization costs (4.0 ¢/l). A reduction in the number of operators of 50 % (1.5 operators) and 67 % (1 operator) would yield a 19 and 25.5 % reduction in total costs, respectively. However, an automatic line would be required to be installed for loading and unloading the product which will increase the equipment cost by 10–35 %.

Depreciation and Other Administration Costs

The shelf-life of the processing equipment was estimated to be 10 years with the annual depreciation costs accounting for $13,000 and $508,000 in the case of thermal and HPP, respectively. Maintenance was applied as a factor of 2 % to the capital cost of the thermal system ($2,560 per year) and factor of 8 % to the high pressure pasteurization system ($400,000 per year) to account for the higher cost of the spare parts and labor and the vessel replacement needed after a period of cycles (200,000–500,000 cycles). Other administration charges (2.5 %) were applied to the capital costs to account for insurance (1 %), local taxes (1 %) and factory expenses (0.5 %). Overall depreciation, maintenance and other administration charges for the thermal and HPP system accounted for 2 % and 30 % of the overall production costs (0.04 and 3.2 ¢/l), respectively.

Total Production Costs

The total cost of production of 1 l of orange juice by thermal pasteurization was estimated to be 1.5 ¢/l, whereas HPP was 10.7 ¢/l which corresponds to 7-fold higher than thermal pasteurization. In case of the PEF system, the overall cost was estimated to be 3.7 ¢/l (2.5-fold higher). These costs are estimated for orange juice processing in the US. The absolute costs may vary for other regions. While the additional costs of the nonthermal processes are substantial, consumers may be willing to pay more for higher-quality orange juice produced by these new processes.

Tonello (2011) reported some figures for the cost of HPP in different food products; the percentages for labor (10–40 %), energy (2–3 %), maintenance (22–33 %) and depreciation (65–75 %) were of the same order as those presented in this study. Cost of HPP (4.4–10.4 ¢/kg for a 420-l system) was also within the range of the cost estimated in this study. Mujica-Paz et al. (2011) estimated the cost for HPP (600 MPa for 3 min, 300-l vessel and 60 % of vessel filling ratio) of 15.7 ¢/kg for a 1,440 kg/h of production. The slightly higher number with respect to our study is due to the lower throughput based on a longer cycle time. Other authors have estimated the overall costs of the HPP between 0.1 and 0.2 ¢/kg (Ludikhuyze et al. 2002), 10 and 50 ¢/l (Thakur and Nelson 1998) or 8 and 22 ¢/l (Hernando-Saiz et al. 2008). Our estimates are within the low range of the cost interval estimated by other studies. This may be due to the higher volumes of the pressure vessels used here and shorter cycle times allowing for a higher throughput.

Environmental Impact: CO_2 Production

Table 3 shows the environmental impact of the three pasteurization systems in terms of greenhouse gas CO_2 equivalent emission. An 80 % factor was used for the natural gas conversion to steam energy in the boiler. This value will vary depending on the design and operation of a specific boiler (Babcock and Wilcox Company 2005). The electrical energy used to generate the steam was obtained by using a conversion factor 0.44 kW h/1,000 kg steam. This factor was estimated by assuming an on-site natural gas steam generating system producing 40,300 kg steam/h that required 14.8 kW h of total electrical energy (boiler fans, boiler feed water pumps and miscellaneous electrical power for lighting, controls and boiler feed water preparation systems) and then dividing by the kg steam/h. The total cooling water needed in the process was

Table 3 Environmental impact of high pressure, pulsed electric field and thermal processes

Process parameters	Unit of measure	Thermal	PEF	High pressure
Steam consumption	kg/year	284,000		
Cooling water consumption	kg/year		79,131,000	
Natural gas requirements[a]	kg/year	19,000		
Electricity requirements (steam)[b]	kW/year	125		
Electricity requirements (cooling water)[b]	kW/year		55,000	
Electricity requirements (equipment)	kW/year	38,100	865,000	1,020,000
Total electricity consumption	kW/year	38,200	920,000	1,020,000
Subtotal CO_2 equivalent emissions (electricity)[b]	kg CO_2/year	29,000	700,000	773,000
Subtotal CO_2 equivalent emissions (natural gas)[b]	kg CO_2/year	70,000		
Total CO_2 equivalent emissions	kg CO_2/year	90,000	700,000	773,000

[a] With 80 % conversion efficiency factor

[b] Conversion factors obtained from the US Department of Energy

converted to electricity (kW h) by modeling a cooling tower water system processing 9,670 l water/min that required approximately 128 kW h (cooling tower fans, cooling water pumps and water treatment system). Conversion factors to estimate CO_2 equivalent emissions per kW h, precombustion factor fuel to building CO_2 per 1,000 m^3 of natural gas, and on-site combustion factor of CO_2 per 1,000 m^3 of natural gas were obtained from the US Department of Energy (Deru and Torcellini 2007).

As we can see in the table, equivalent CO_2 annual emission for thermal pasteurization was about 90,000 kg whereas CO_2 emission for PEF and HPP systems were similar with the value for the high pressure system slightly higher (700,000 vs. 773,000 kg). This is equivalent to an increase of 777–858 % with respect to the thermal system. This is the first study to estimate the environmental impact of new processing technologies. In a recent study, Pereira and Vicente (2010) claimed that PEF and HPP systems avoid using natural gas and boilers due to the elimination of thermal processing. The lack of steam generators could also diminish wastewater, thus increasing water and energy savings. They also claimed the partial reduction of cooling system requirements that represent approximately 50 % of the total electricity consumption. It may be possible to claim these new technologies as waste-free processes; however, in our study, despite the lower cooling requirements, nonthermal processing still generated more equivalent CO_2 emissions than thermal pasteurization due to the higher electricity consumption.

Sensitivity Analysis

A sensitivity analysis was conducted to estimate the impact of processing volume (500–5,500 l/h) on the total cost of pasteurizing a liter of orange juice (Fig. 4). In the case of the PEF system, the impact of processing volume (1,000–5,500 l/h) on the total processing costs was estimated. As can be seen in Fig. 4a, doubling the production size (from 1,000 to 2,000 l/h) reduced the total costs by nearly 50 %, whereas an increase of 3- and 5-fold (from 1,000 to 3,000 and 5,000 l/h) reduced the overall costs 60 % and 75 %, respectively.

In case of HPP system, processing volumes from 500 to 3,000 l/h were used to study the impact of production size on

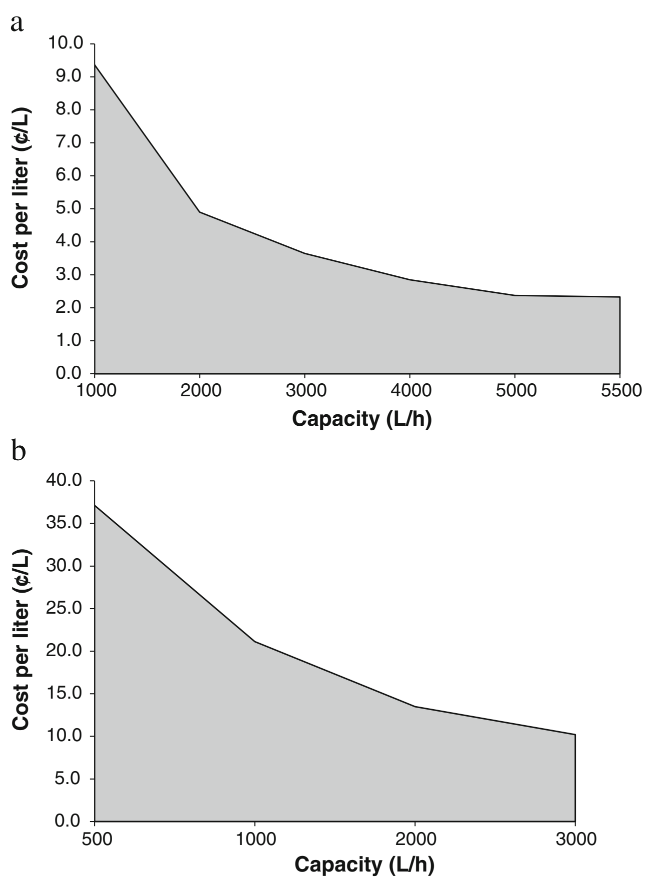

Fig. 4 Sensitivity analysis of PEF (**a**) and HPP processes (**b**) by changing the overall throughput

total processing costs (Fig. 4b). An increase in production size of 2-, 4- and 6-fold (from 500 to 1,000, 2,000 and 3,000 l/h) reduced the overall costs by 43–72 %. This could be accomplished by reducing the cycle time or increasing the vessel filling ratio by a better package design. In a study conducted by Dalsgaard and Abbotts (2003), the authors showed that increasing production amounts was the most profitable way to decrease energy consumption per produced unit (as an example a reduction in energy consumption from above 2,000 kW h/ton to above 550 kW h/ton by increasing production from 500 to 2,500 tons/month in a Danish poultry company).

Conclusions

Thermal pasteurization is a mature and widely used process where design has been refined and overall costs reduced over time. PEF and high pressure pasteurization processes are new technologies and the capital cost should decrease in the future as they see wider use in the food industry. In each of the three pasteurization processes, costs are driven by energy consumption, capital cost and labor required to support the process. High pressure is more costly than PEF yet its implementation in the food industry has been widely demonstrated. Other factors besides cost seem to influence the purchase decision by companies. Cost estimates depend on the region, energy source and food product; this study only provides a general estimate of the difference among thermal and nonthermal processing. Nonthermal processing technologies are more costly and have higher environmental impact (in terms of CO_2 production) than traditional thermal pasteurization.

Acknowledgments The authors are grateful to the Fundación Española para la Ciencia y la Tecnología (FECYT) from Ministerio de Innovación y Ciencia from Spain for providing the postdoctoral grant to Dr. Fernando Sampedro. The authors acknowledge Drs. Tony Jin and Brendan Niemira for their helpful reviews of the final draft. The authors also acknowledge Mr. Joseph Sites for providing technical assistance with the HPP unit and Mr. Michael Kempkes of Diversified Technologies, Inc. (Bedford, MA), Ms. Carole Tonello of Hiperbaric S.A. (Burgos, Spain) and Mr. Nick de Pinto of Avure Technologies (Franklin, TN) for their valuable data.

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